GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 10, PAGES 1205-1208, MAY 15, 1995

Preliminary results from the Sprites94 aircraft campaign: 1. Red sprites

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Abstract. The dual jet aircraft Sprites94 campaign yielded the first color imagery and unambiguously triangulated physical dimensions and heights of upper atmospheric optical emissions associated with thunderstorm systems. Low light level television images, in both color and in black and white (B/W), obtained during the campaign show that there are at least two distinctively different types of optical emissions spanning part or all of the distance between the anvil tops and the ionosphere. The first of these emissions, dubbed "sprites" after their elusive nature, are luminous structures of brief (< 16 ms) duration with a red main body that typically spans the altitude range 50-90 km, and possessing lateral dimensions of 5-30 km. Faint bluish tendrils often extend downward from the main body of sprites, occasionally appearing to reach cloud tops near 20 km. In this paper the principal characteristics of red sprites as observed during the Sprites94 campaign are described. The second distinctive type of emissions, "blue jets," are described in a companion paper [*Wescott et al.*, this issue].

Introduction and Background

Accounts of brief optical emissions above thunderstorms go back more than a century [see, e.g., *Boys*, 1926; *Malan*, 1937; *Vaughan and Vonnegut*, 1989], and *Wilson* [1956] has discussed the possibility of lightning discharges extending upward from cloud tops. However, it has not been until the past few years that images of discharge events have been obtained. *Franz et al.* [1990] recorded the first low light level television images of these events, and estimated that they extended to altitudes of 34 km or higher. Following this observation *Vaughan et al.* [1992] and *Boeck et al.* [1994] reported television observations from the space shuttle of a number, now approaching twenty, of what appear to be similar events above thunderstorms on the limb of the planet.

During the summers of 1993-1994 there occurred a marked increase in the quantity and quality of reports of this phenomenon. Using a low light level All Sky television system, *Sentman and Wescott* [1993] imaged nineteen examples of these events during a single flight of NASA's DC-8 Airborne Laboratory over thunderstorms in Iowa, Nebraska and Kansas in July, 1993. They estimated the most probable terminal heights of the events to be 60 km, with error bars extending to 100 km. The duration was estimated to be 16 ms or less, and the brightness was calculated from comparison with stellar brightness to be 25-50 kR, roughly that of moderately bright aurorae. The occurrence rate was estimated to be approximately 1 for every 200-300 cloud-to-ground strokes.

Paper number 95GL00583
0094-8534/95/95GL-00583$03.00

In a more sustained ground-based program, *Lyons* [1994 a,b] obtained B/W images of high altitude flashes above storm systems in Nebraska and Kansas in July and August, 1993, increasing the inventory of recorded events to more than six hundred. Similarly, *Winckler* [1994], using low light level B/W cameras, recorded about 150 events above intense thunderstorm systems to the south of his recording station in Minnesota in July-August, 1993. Recent summaries of observations before the summer campaigns of 1994 are given by *Boeck et al.* [1994] and *Lyons* [1994a].

The high altitude luminous structures imaged in the above reports have been variously referred to in the literature as upward or cloud-to-ionosphere lightning, cloud-to-ionosphere or cloud-to-stratosphere discharges. Such appellations suggest possibly unwarranted parallels to normal tropospheric electrical discharge activity, or imply specific production mechanisms about which at present little is known. We therefore adopted the non judgmental name "sprites" for these events after their elusive qualities. Hence, the name "Sprites94" for our observation campaign.

In this paper we report preliminary results of observations of sprites recorded during the Sprites94 aircraft campaign of June-July, 1994. The principal objectives of the research were to obtain color images of the events, to triangulate their dimensions and terminal altitudes accurately, to record their optical waveforms and emission spectra, and to study their ELF/VLF electromagnetic signatures. During the campaign a second type of emission, distinct from sprites, was also unexpectedly observed. In a companion paper *Wescott et al.* [this issue] describe these "blue jets." *Sentman and Wescott* [1994] have previously released a short video containing selected sequences of television images obtained during the campaign.

The Sprites94 Aircraft Campaign

Two jet aircraft were used as imaging platforms to provide the high altitude observing vantages and angular separation necessary for triangulation studies. Flight missions were conducted out of Oklahoma City after dusk on the dates listed in Table 1 to areas of active thunderstorm activity in the Midwest. The dates of the campaign interval were chosen to provide for moon down observing conditions necessary for low light camera operation during 2200-0200 Local Time when thunderstorm activity was at a maximum.

Aircraft. The two corporate jet aircraft used to make the observations were a Rockwell Jet Commander and an Israel Aircraft Industries Westwind 2, both leased from Aero Air, Inc. of Hillsboro, Oregon. Observations were conducted at altitudes 40,000-42,000 ft (12.2-12.8 km) at speeds of 425 knots (790 km/hr). On a typical flight mission the aircraft flew in a loose

Table 1 Sprites94 Flight Missions (1994)

UT Date	Area of Thunderstorm Observation	Hr. Data
29 Jun	Colorado, Texas Panhandle	1.0
30 Jun	Oklahoma to Nabraska	2.5
1 Jul	Central Arkansas	2.0
3 Jul	Gulf Coast, Florida Panhandle	3.0
4 Jul	New Mexico to Kansas	3.0
5 Jul	Nebraska to Colorado	1.25
6 Jul	Oklahoma to Texas Panhandle	2.75
7 Jul	Iowa, Nebraska, Colorado	2.0
10 Jul	Texas Panhandle	2.0
11 Jul	South Dakoda	2.0
12 Jul	Eastern/Central Texas	1.25
13 Jul	Eastern Colorado	2.0

trail formation, with the Jet Commander leading the Westwind 2 by 10-75 km.

Instrumentation. The aircraft were both fitted on the right side with factory new plastic windows. Above 450 nm their transmissivity was about 90%, and at 400 nm and 390 nm the transmissivity fell to 75% and 51%, respectively. The primary camera systems utilized during the campaign are described below. Additionally, the Jet Commander had a pair of baffled photomultiplier tubes to detect flash waveforms and propagation velocity, and a television slit spectrograph. The Westwind 2 carried an intensified B/W All Sky camera as a backup system. Finally, an ELF/VLF detector was deployed on the ground northwest of Oklahoma City to record electromagnetic wave forms associated with sprites.

Both aircraft were equipped with Trimble model Six-Vee 6 Global Positioning Satellite (GPS) navigation systems to track aircraft position and speed. GPS information was recorded directly onto the video images using a Horita model GPS-2 SMPTE time code generator. The GPS signals were fed to a master sync generator to synchronize the horizontal and vertical sweeps of all camera systems. This permitted accurate triangulation and stereoscopic visualization of images simultaneously captured from the separate aircraft. Position, altitude, and dimension measurements of the sprites subsequently obtained from triangulation calculations were accurate to about 2-3 km. Measured GPS timing and camera synchronization accuracy was ±32 μs, absolute.

The measurements reported here were obtained using the following instruments.

Wide Angle Low Light Level Black and White Cameras We used Dage-MTI VE-1000 SIT B/W cameras, which have a sensitivity of 1.6 x 10^{-7} W-m^{-2} at 550 nm and 300 lines resolution. The cameras were equipped with Kinoptik 5.7 mm f/1.8 TEGEA wide angle lenses, with 92°H x 69°V fields of view (FOV). One Dage camera was on each aircraft. The video images from these cameras were recorded at 60 fields per second (fps) on Sony U-Matic 3/4 inch tape recorders, along with GPS timing and navigational information.

Intensified Color Camera The color camera on the Westwind 2 was an Ikegami HL-51S with 2,000,000 ISO equivalent and sensitivity of approximately 2 kR [*Ikegami*, 1984; *Hallinan*, 1988]. The camera has three separate SIT subsystems with red, green and blue responses that maximize at approximately 600 nm, 530 nm, and 450 nm, respectively [see *Wescott et al.*, this issue]. For Sprites94 the camera was equipped with a Canon PV10X 12B2 12-120 mm zoom lens, operated at 12 mm and f/2.0, yielding a 55°H x 43°V FOV. The images from the Ikegami camera system were recorded at 60 fps on a Sony Betacam SP recorder, along with GPS timing and navigation information.

A ground support station was established at the National Severe Storms Laboratory (NSSL) for the Sprites94 campaign to provide real-time updates from the National Lightning Detection Network (NLDN). Radar and GOES 7 infrared weather maps from Weather Services, International (WSI) and lightning maps from the NLDN were collected periodically and uploaded to the Jet Commander via the AGRAS and SKYHOOK communications systems.

Preliminary Results

An estimated 500 separate upper atmospheric optical events were recorded during the twelve flight missions listed in Table 1. More than half of these events were imaged simultaneously from both aircraft, and more than half by the color camera.

Figure 1 shows two events recorded during the campaign. One of the first newly documentable results of the observations, as shown here in the right panels, is that the main upper portion of sprites is predominantly red. In the images from the color camera the main body of the sprite registers primarily in the red channel. Very weak or no signatures are present in the blue and green channels.

The luminous regions appear to range from small single or multiple vertically elongated spots to spots with faint extensions above and below, to bright groupings which extend from the cloud tops to altitudes up to 95 km. The concentration of the luminosity into distinctive spatial features tend to occur within a limited range of altitudes and is sufficiently repeatable to warrant consideration as "unit" elements. We refer to these unit elements as "sprites" for reasons mentioned above.

A preliminary anatomy of sprites may be constructed based on these features. Results of detailed triangulations of the positions of the features of 29 separate sprites or clusters of sprites reveal that the brightest region, the "head," lies within the bracketed range of altitudes 66-74 km (± 4 km). Above the head there is often a faint red glow or wispy structure ("hair") separated from the bright head by a dark band ("hairline"), and extending to 88±5 km. On two of the sprite clusters studied in detail the terminal height of the hair exceeded 95 km. The hair may occasionally exhibit a weak horizontal dark band at 79±4 km. On some of the brighter sprites, as shown in Figure 1, there is a dark band ("collar") beneath the head at 66± 4 km, below which extend tendril-like filamentary forms. The color of the tendrils is red just below the collar, gradually merging into blue with distance downward. The tendrils have been triangulated to reach downward to as low as 40 km, below which Rayleigh scattering and camera blooming from intracloud lightning prevents identification of structural detail necessary to perform a triangulation. Figure 2 shows our preliminary anatomy of the basic sprite form, and its altitude relationship to atmospheric temperature and typical night time electron density profiles.

Sprites rarely appear singly, usually occurring in clusters of two, three or more. Some of the very large events, such as in Figure 1, seem to be tightly packed clusters of many individual sprites. The brightest regions of these "compound sprites" typically saturated the B/W images, and in some cases the color images, as well (e.g., the white central portion of the sprites in Figure 1). Many sprite events consist of multiple,

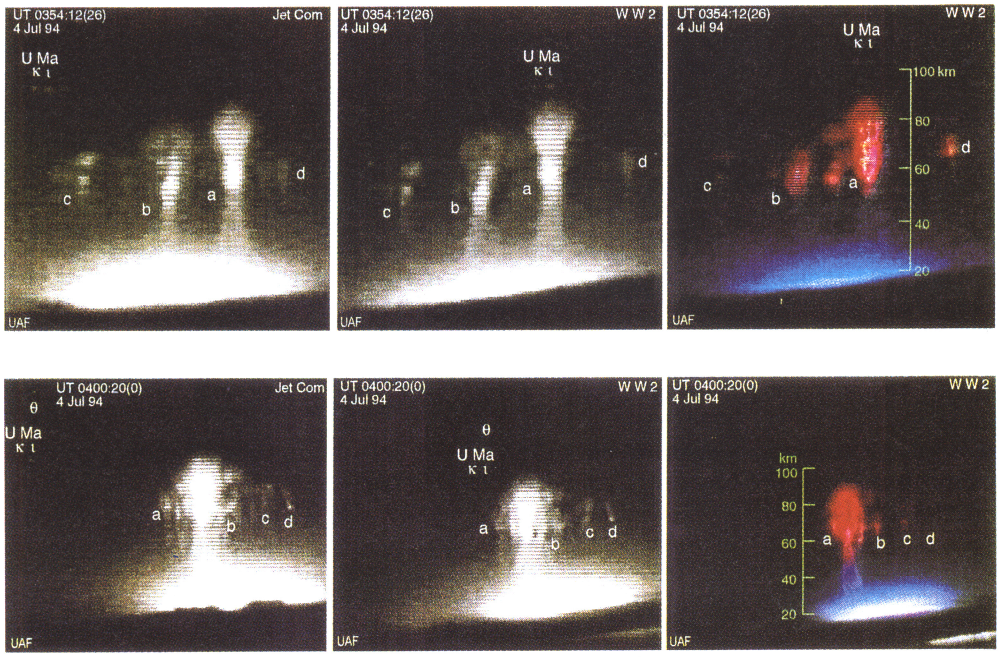

Figure 1. Two separate sprite events observed on 4 July, 1994. On each row the left-hand B/W image was taken from the Jet Commander, while the center B/W image and the right hand color images show the same event from the Westwind 2 aircraft. Selected stars within the respective fields of view have been labeled. The altitude scale in the color image refers to the brightest feature. *Top Row* UT 0345:12(video frame 25). A cluster of sprites. The parallax of stars in the constellation Ursa Major relative to the sprites may be seen by comparing the B/W images. *Bottom Row* UT 0400:20(video frame 0) This large compound sprite was one of the largest observed. Note the blue/purple tendrils. Aircraft separation for both events was about 50 km.

spatially distinct sprites, which may be laterally distributed across distances 40 km or more. Figure 3 shows an example of a cluster of three distinct sprites that were imaged simultaneously from the two aircraft while studying a storm over the Texas panhandle on the night of 6 July, 1994. The point on the ground below each of the individual sprites is indicated in the accompanying map. The sprites occurred on the backside of the frontal storm system that was moving

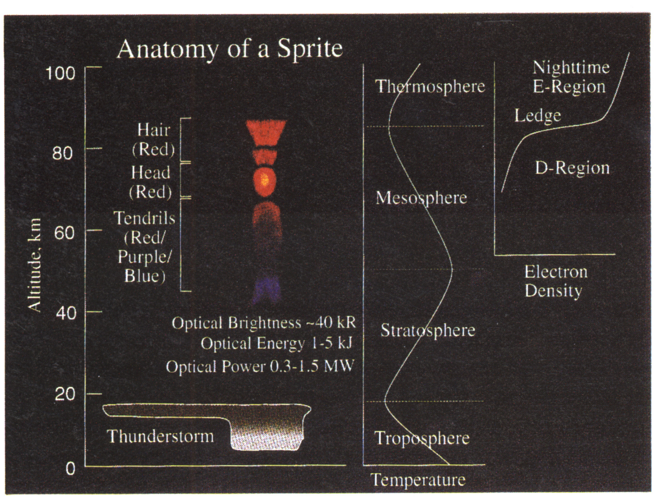

Figure 2. Anatomy of a "unit" sprite and its altitude relationship to atmospheric temperature and typical night time electron density profiles. More complicated compound sprites and sprite clusters consist of groupings of the unit sprite at various densities.

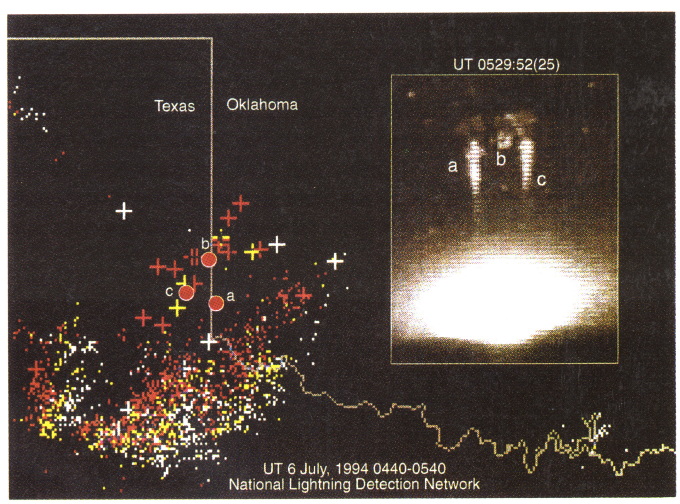

Figure 3. Spatial location of the individual sprites in the event of UT July 6 0529:52(video frame 25). The location of the sprites, indicated by large red dots, is projected onto a time/polarity color coded map of cloud to ground lightning as recorded by the National Lightning Detection Network. Positive ground strokes are indicated by pluses, negative strokes by dots. Strokes occurring, relative to the time the map was stored (UT 0540), are coded as white (0-15 min), yellow (15-30 min) or red (30-60 min). The sprites are seen to be laterally distributed over distances comparable to the terminal heights of the events (~100 km).

through the Texas panhandle. The majority of sprites observed were similarly located well behind the associated storm fronts, in regions where positive cloud-to-ground strokes were dominant.

The red, bright portions of sprites and their extensions above and below occur predominantly within the altitude range 50-95 km, thus making sprites primarily a mesospheric D-Region phenomenon. The lateral dimension of "unit" sprites is typically 5-10 km, corresponding to volumes that may exceed 10^3 km^3. Compound sprites and sprite clusters may occupy volumes greater than 10^4 km^3.

Detailed analysis of the apparent brightness of several separate unit sprites determined by comparison to stellar brightness references [*Wescott et al.*, this issue] yields a maximum brightness of roughly 600 kR within the sprite. When averaged over the dimmer outer portions of the sprite the mean brightness is about 50 kR, consistent with our original brightness estimates [*Sentman and Wescott*, 1993] of 10-50 kR. If we assume the optical emission is centered at 600 nm and spatially distributed uniformly throughout a mean estimated emission volume of 2000 km^3, this translates into a total optical energy of 1-5 kJ per event. Assuming a duration of 3 ms the instantaneous optical power of these unit sprites is therefore in the range 0.3-1.5 MW. Energy and instantaneous optical power of large sprite clusters and compound sprites my exceed these figures by an order of magnitude or more, i.e., 10-50 kJ and 3-15 MW, respectively.

Summary

Results of the present study may be summerized as follows.

1. Sprites are a mesospheric/D-region phenomenon. They reach upward to an average maximum height of approximately 88 km, with an rms altitude spread of about 5 km. In the largest and brightest examples observed terminal heights exceeded 95 km, placing the tops of these events firmly within the lower regions of the ionospheric E-region.
2. Sprites are predominantly red. The brightest region of a unit sprite, its "head," lies between characteristic altitudes of 66 km and 74 km. Above the head there is often a dark band ("hairline") above which a faint, wispy red glow ("hair") is observed to splay upward and outward toward terminal altitude. Beneath the head there sometimes occurs a dark band ("collar") at 66± 4 km below which faint tendrils may extend downward to altitudes of 40-50 km, changing from red near the collar to blue at their lowest extremities.
3. Sprites may occur singly, but more typically occur in clusters of two or more. Clusters may be tightly packed together into large structures 40 km or more across, or loosely spread out into distended structures of spatially separated sprites. Onset of luminance occurs simultaneously (within video resolution, 16 ms) across the cluster as a whole, coincident with the occurrence of cloud lightning below. All elements of the cluster typically decay in unison over 3-5 video frames (100-160 ms), but most of this decay time may be attributed to image lag of the SIT cameras.
4. Sprites seem preferentially to occur on the backside of frontal storm systems, and occur in regions of positive lightning ground strokes.
5. The total optical energy in a typical unit sprite is estimated to be 1-5 kJ, and the corresponding instantaneous power is 0.5-2.5 MW. The energy and power of compound sprites and sprite clusters may exceed these values by an order of magnitude.

Acknowledgments: We thank Mary Mellott and Rick Howard of Code SS, NASA Headquarters, for support and encouragement in this project, and Andy Cameron of the Earth Sciences Office for his invaluable assistance. We thank Aero Air, Inc., Hillsboro, Oregon for use of their aircraft; the enthusiasm and professional skills of Jeff Tobolski, Norm Ralston, Mark Satterwhite, and Chuck McWilliams made the success of the aircraft operations possible. We thank Dave Rust of the National Severe Storms Laboratory, Norman, Oklahoma for his assistance and ground station support. We are grateful to H. Stenbaek-Nielsen for providing us with triangulation routines. Finally, we acknowledge useful discussions with Walter Lyons, ASTeR, Inc., Ft. Collins Colorado, and Earle Williams, MIT. This research was supported by NASA Grant NAG5-5019 and National Science Foundation Grant ATM-9217161.

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(Received November 11, 1994; revised February 6, 1995; accepted February 17, 1995)